DAMAGE DEVELOPMENT IN WOVEN GLASS FIBRE COMPOSITES WITH TOUGH THERMOSET MATRIX

K. A. M. Vallons[1]*, R. Drozdzak[2], M. Charret[2], S. V. Lomov[1]

[1] *KULeuven, dept. of Materials Engineering, Leuven, Belgium*

[2] *Telene SAS, Bondues, France*

*corresponding author: Katleen.vallons@mtm.kuleuven.be

Plain weave glass fibre composites with poly-dicyclopentadiene (PDCPD) and epoxy matrices were subjected to static tensile tests while monitoring damage development. Tensile fatigue tests were periodically interrupted to allow for damage assessment in the samples. Damage during static tensile loading in the epoxy composite followed the characteristic pattern. In the PDCPD composite, however, the formation of damage was markedly reduced. In tensile fatigue, the variation in fatigue life was found to be significantly smaller for the PDCPD composite than for the epoxy composite. As for the static tests, the characteristic damage development pattern as observed in the epoxy laminate was much less pronounced in the PDCPD composite. The reduction in damage in the PDCPD laminate resulted in less severe stiffness loss during the tests.

INTRODUCTION

Several studies e.g. [1-3] have described the damage evolution under tensile loading in woven fabric composites and its influence on the composite modulus. Qualitatively, the behaviour is very similar for quasi-static and fatigue loading, and can be seen as a three stage process, similar to what is commonly defined for multidirectional 'UD' laminates. In a first stage, the modulus decreases rather rapidly, as a multitude of transverse (weft) matrix cracks are formed, preferentially starting at the cross-over points of warp and weft yarns in the fabric. After this initial stage, not many new transverse cracks are created and a kind of saturation state is reached. Later in the test, cracks occur also in the longitudinal (warp) direction, and local delaminations, called 'meta-delaminations' are created at the warp and weft interlacing points. In this stage, the modulus decreases gradually. In the final stage of fatigue, the meta-delaminations grow and delaminations between the different fabric layers are formed. This large-scale delamination leads to final failure and the modulus again decreases rapidly.

This damage pattern is known to be influenced by the properties of the constituents of the composite. It has been reported that a higher matrix fracture toughness will delay the initiation and growth of matrix cracks in the initial fatigue stage. Also the formation of meta-delaminations is suppressed and delayed [4].

In the present study, quasi-static and fatigue tensile behaviour was analysed for two types of plain weave glass fibre composites. The reference material was based on a standard (brittle) epoxy matrix. The second type used a tough thermoset poly-dicyclopentadiene (PDCPD) formulation for the matrix. PDCPD shows a number of interesting properties for use in composite materials, some of which are listed in Table 1. The goal of the work was to compare the development of damage in the two materials and assess the influence on the modulus.

MATERIALS AND EXPERIMENTS

Plain weaves based on two types of glass fibre rovings were used: T73, which is compatible with PDCPD resin and T72, which is compatible with epoxy resin. The fabrics had an areal density of 800 g/m². The matrix materials used for this study were a modified high T_g PDCPD formulation (indicated below as F2.06) containing a conomer, supplied by Telene SAS, and a standard epoxy resin (epikote 828 LVEL with Dyteck DCH 99 hardener). Some properties of the matrix materials are listed in Table 1.

Table 1: Physical, thermal and mechanical properties for the matrices studied in this work.

	PDCPD F2.06	**Epikote 828 LVEL + DCH-99**
Density (kg/dm³)	1.03	1.16
Modulus (GPa)	1.9	3 [5]
Initial viscosity @25°C (Pas)	< 0.01	10-12 [6]
Tensile Strength (MPa)	*60*	75 [5]
Elongation at break (%)	*At yield: 5*	4 [5]
Glass transition temperature (°C)	215	155

Woven fabric laminates were produced by vacuum infusion of 4 layers of glass fibre weave with the F2.06 PDCPD resin and the epoxy resin. The fibre volume fraction for the PDCPD laminate was 53 %, that for the epoxy laminate was 56 %.

Samples with dimensions of 250x25x2.3 mm³ were cut from the laminates and subjected to quasi-static tensile tests with a crosshead speed of 2 mm/min. Strain was measured either by means of digital image correlation (DIC) over a region of 25x25 mm² or by means of an extensometer with a gauge length of 50 mm. The pictures from the DIC analysis were also used to monitor the development of damage during the test. For this, a light source was placed behind the (transparent) samples.

A series of fatigue tests was run on both types of materials with a frequency of 5 Hz and an R-ratio of 0.1. Tests were done at approximately 50, 40, and 30% of the tensile strength. As an indication of the stiffness evolution during fatigue, the chord modulus was determined as the ratio of the difference in load over the difference in displacement for each cycle. The damage evolution in samples tested up to 150 MPa (30 % of the UTS) was monitored by periodically interrupting the tests and taking a transmitted light picture of the samples.

RESULTS AND DISCUSSION

Quasi-static tension

The results of the tensile tests are shown in **Error! Not a valid bookmark self-reference.**. No significant difference between the two materials was measured in terms of stiffness, even after normalizing the results to the same fibre volume fraction (50 %). The strength as-measured also showed no difference. However, after normalization, the strength of the PDCPD laminate was found to be about 9 % higher than that of the epoxy composite (p=0.03). The failure strain for the epoxy samples was marginally larger than that of the PDCPD composite. This may be explained by the pronounced loss in stiffness of the epoxy samples near the end of the test, caused by the build-up of extensive delamination damage.

Table 2: Tensile strength, modulus and failure strain for the two laminates, and the normalised values (fibre volume fraction = 50 %).

Material	PDCPD laminate	Epoxy laminate
Tensile strength (MPa)	516 ± 14	502 ± 33
Tensile modulus (GPa)	23 ± 2	26 ± 3
Normalised modulus (GPa)	22 ± 2	25 ± 3
Normalised strength (MPa)	487± 13	448 ± 29
Failure strain (%)	2.7 ± 0.1	2.9 ± 0.1

Figure 1 shows the development of damage during the tensile tests for different strains for both materials. Typical tensile curves for the two materials are shown in Figure 2. Although both laminates are produced from weaves with equal characteristics (areal density, ends, picks), the pictures indicate a marked difference in damage behaviour.

The epoxy composite exhibits the classical damage pattern found for woven fabric composites with a brittle matrix as outlined in the introduction: first, and early in the test, numerous transverse matrix cracks are formed. The number and length of these cracks rapidly increase up to a strain of about 1.5-2 %. At that point, longitudinal cracks can be seen, and at the intersection of longitudinal and transversal cracks, the onset of delamination can be observed. These local delaminations are distributed over the whole gage length of the sample and are located at the 'interlacing' points of the fibre bundles in the woven fabric. These delaminations grow and coalesce into larger delaminations and finally the whole composite fails by major delamination and fibre failure. Failure in this type of composite was very dispersed (not localized). The development of this extensive damage during the test is reflected in the tensile curve: around the point where transverse cracking starts, a first decrease in slope and thus stiffness is observed. A second decrease in slope is seen around the point when delaminations are starting to form.

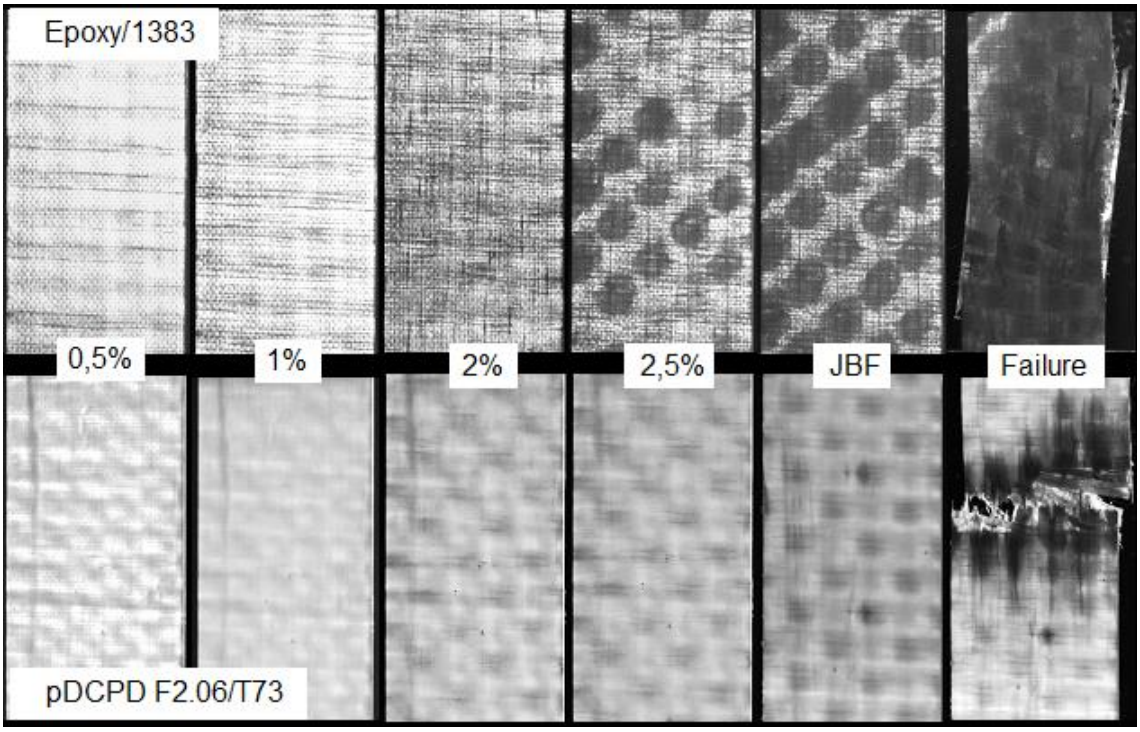

Figure 1:Transmitted light pictures of the damage development during a static tensile test.

The PDCPD composite, on the other hand, does not show any damage up to around 1 % of strain, after which a very limited amount of short, localized transverse cracks start to develop. They are typically limited to about one fibre bundle width. Later, short longitudinal cracks are also observed. The matrix cracking is accompanied by only a very slight and gradual decrease in slope of the tensile curve. The first real signs of delamination in the PDCPD sample are in the second to last picture, which was taken approximately 1 second before failure (called JBF in the figure), i.e. at a strain virtually equal to the failure strain. The image also shows that final failure in this material is, in contrast to the epoxy laminate, very localized and consists of fibre failure with a very limited amount of delamination that is concentrated around the fibre failure region. In fact, the failure mode resembles that which is typically observed for woven composites with a thermoplastic matrix, e.g. for a glass-PP composite in [7]. Because of the absence of extensive matrix cracking and delamination in the PDCPD samples before the final failure there is no significant decrease of the modulus up to the end of the test. The higher resistance against damage development in the PDCPD laminate can explain the slightly higher tensile strength that was observed.

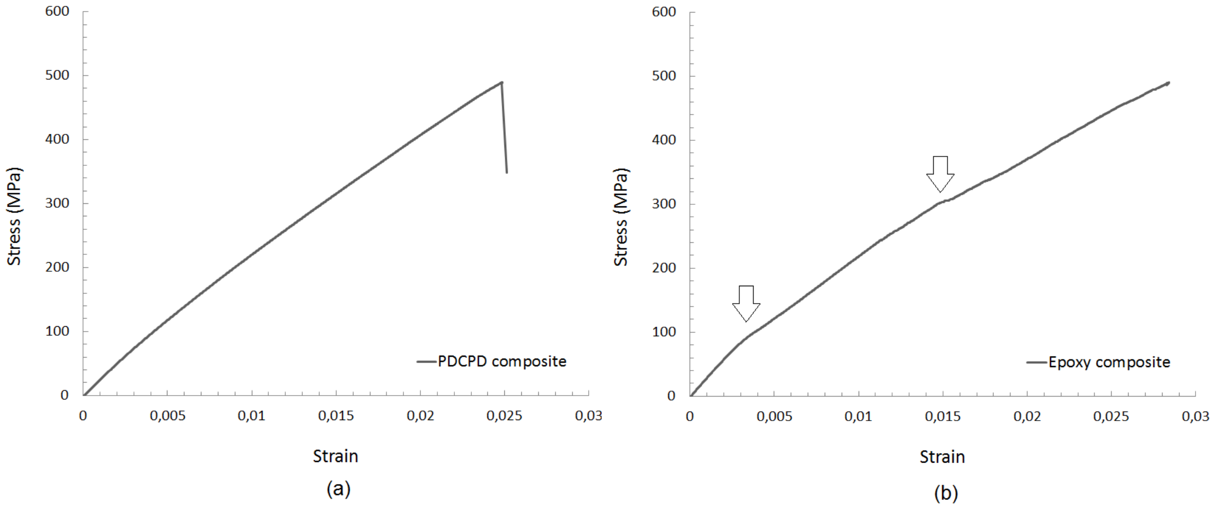

Figure 2: Typical tensile curves for the PDCPD (a) and the Epoxy (b) composites.

Tensile fatigue

The fatigue life data are shown on the graph of Figure 3. The fatigue life data for the PDCPD composite are somewhat higher than those for the epoxy composite results, although strictly speaking the difference in average fatigue life is statistically not significant ($p=0.06$). The improvement in average fatigue life that is suggested by these results is of the same order as that which was found for composites with toughened epoxy matrices e.g. [8-10].

For all tested load levels, the variation in fatigue life for the PDCPD composite is much smaller than that for the epoxy composite. For a certain fatigue load level, the difference between the lowest and highest observed fatigue life is about a factor ten for the epoxy composite (i.e. one order of magnitude, which is in line with what is commonly observed for epoxy composites), while for the PDCPD laminate this difference is typically less than a factor three.

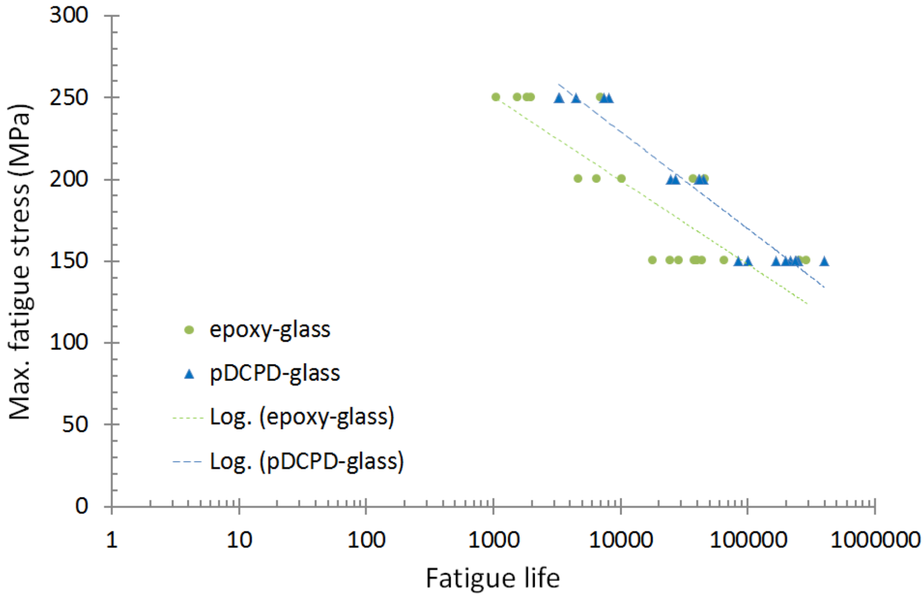

Figure 3: Fatigue life curves for the PDCPD and Epoxy composites

Figure 4 shows the evolution of damage in samples fatigue tested up to 30% of the UTS. After 100 cycles, clear transverse cracks can already be seen in the epoxy composite. At this moment, only a very limited amount of short, localised cracks is found in the PDCPD composite. As the number of cycles increases, short longitudinal cracks are also created. After around 1000 cycles, the onset of local delamination is observed for the epoxy composite on the yarn interlacing sites in the weave, while in the PDCPD composite there is no sign of delaminations at that time. At 10 000 cycles, starting delaminations are also observed in the PDCPD composite. As the number of cycles increases, extensive areas of delaminations are formed in the epoxy composite, while the progression of this type of damage is much slower in the PDCPD composite and no large-scale delamination is noted up to final failure. As in the static tests, the final failure in the epoxy composite was very dispersed, while in the PDCPD composite it was rather localised.

The difference in the extent of the developed damage is reflected in the modulus decrease (Figure 5). In most of the epoxy samples, a stiffness degradation of about 20% was measured at the onset of final failure. In the PDCPD samples, the decrease was typically about 5-10 %. The overall damage evolution in the two materials is in general very similar to that during a static tensile test, although there does seem to be a slightly higher degree of (localised) delamination in the PDCPD composite during fatigue than during static testing.

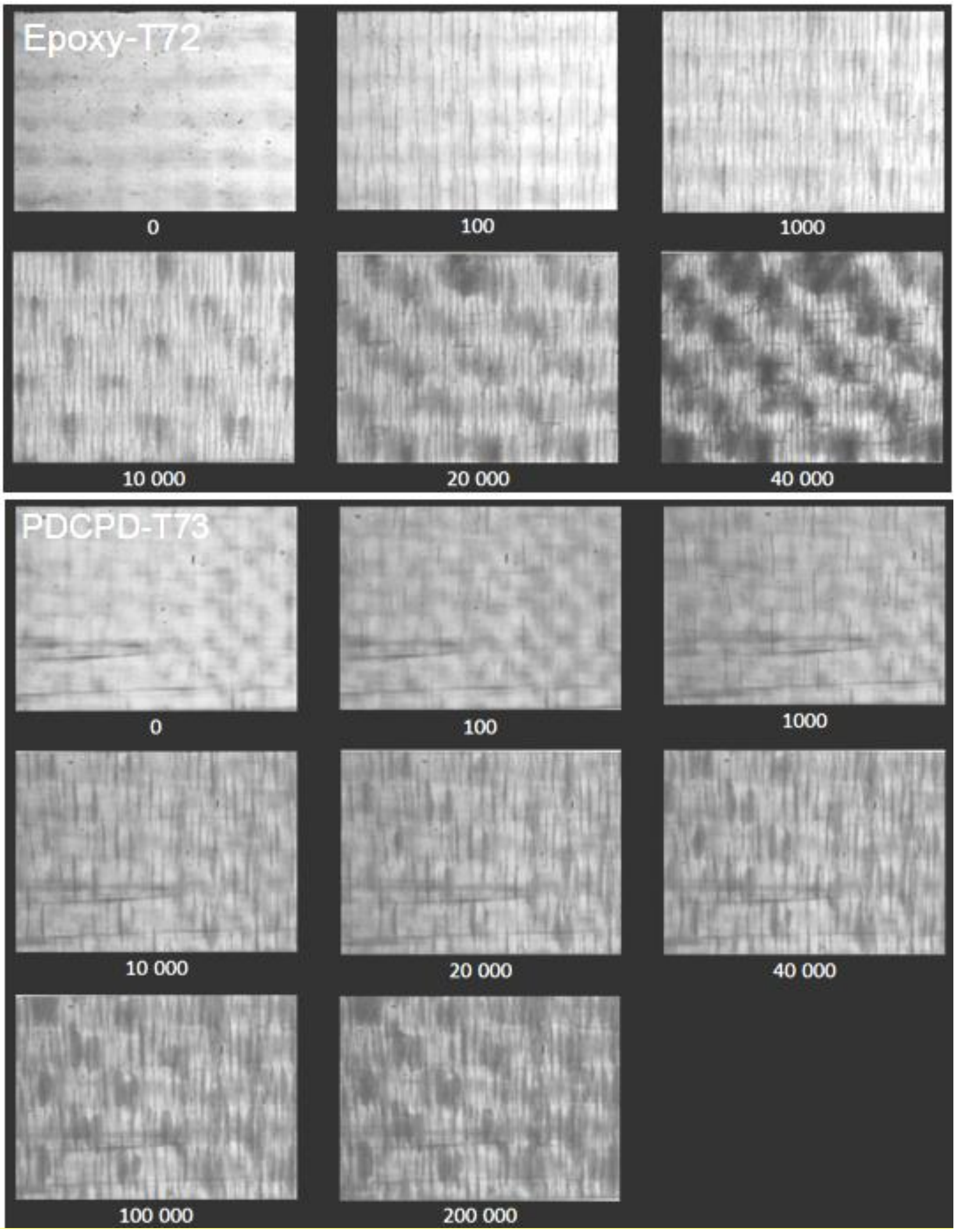

Figure 4: Damage development during fatigue up to 30% of the UTS. (tensile direction is horizontal)

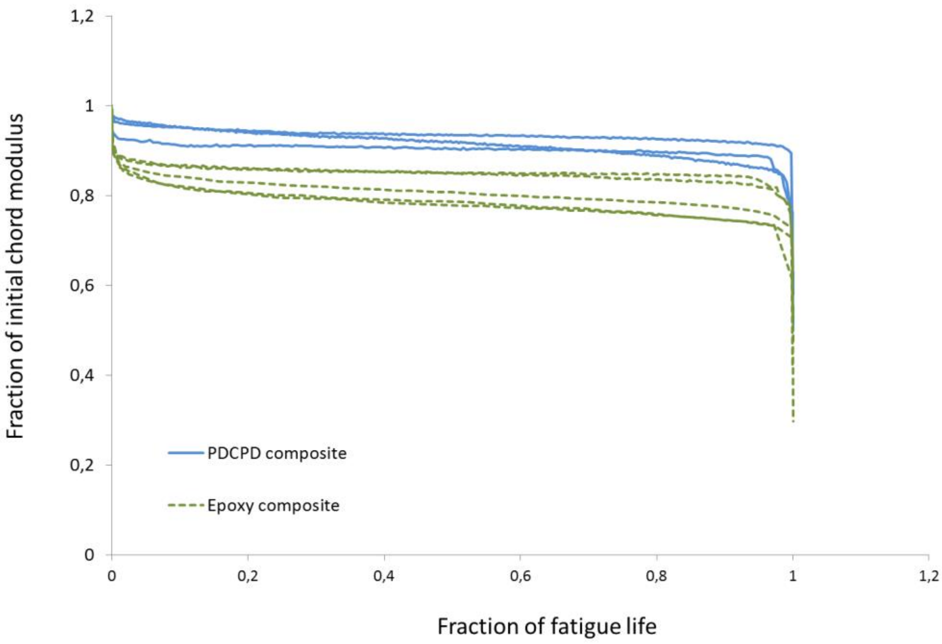

Figure 5: Modulus evolution during fatigue up to 30% of the UTS.

SUMMARY

The results of a comparison of the quasi-static and dynamic tensile behaviour of a glass fibre/epoxy and a glass fibre/PDCPD woven composite are discussed in this paper. A slightly higher static strength was found for the PDCPD composite, which was explained by a much smaller extent of damage development in the samples during the tests. The fatigue life of the PDCPD composite was also slightly higher, and also in this case, the damage developed in these samples was much less pronounced than in the epoxy samples.

In general, the typical damage development pattern seen in traditional (brittle matrix) woven composites seems to be somewhat suppressed by the use of the tougher matrix material. The behaviour is rather similar to what is commonly observed for thermoplastic matrix composites or composites with toughened thermoset matrices.

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